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Recycling Cupola Slag in Concrete as Partial Replacement of Fine Aggregate for Sustainable Construction

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Abstract: In the current study an effort has been made to investigate the impact of cupola slag inclusion, on the mechanical and durability properties of concrete. Different percentages (10%, 20%, 30%, 50%, and 80%) of cupola slag were used to substitute fine aggregate and corresponding results have been observed. Also, different mechanical and durability tests were carried out to check the suitability of replacing natural fine aggregate by cupola slag. Compressive strength was found to be increased by cupola slag inclusion up to a percentage replacement of fine aggregates of 30%, after which further cupola slag addition resulted in a loss of strength. For flexural and tensile strength similar trends were observed. On the other hand, as the amount of cupola inclusion increased from 0% to 80%, a decreasing trend in both water penetration depth and water absorption was observed. Likewise, for all the aforementioned criteria a notable improvement in chloride penetration was observed due to the inclusion of cupola slag. The study basically focuses on present concern regarding industrial waste which poses a risk to the environment. Industrial waste has been utilized in a sustainable manner, as it has shown improvement in properties as compared to ordinary concrete mix. Such type of modified concrete can be employed in harsh exposure conditions as can be found from durability tests. The findings of this study show that cupola slag is a sustainable matter that works well as a partial replacement for natural sand.
Keywords: Cupola Slag, Sustainable Concrete, Waste Utilization, Testing, Fine Aggregate.

I. INTRODUCTION

There are some six thousand cupola furnaces installed in India, with one thousand cupola furnaces located solely in the state of Punjab. The primary clutchs of cupola furnaces within the state are Amritsar, Goraya, Jalandhar, Ludhiana, Patiala and Gobindgarh. Since the late eighteenth century, when the first cupola patent was approved in England, the furnace has continued to remain the pre-eminent diffusing unit in iron foundries. The fundamental activities of a coke-fired cupola have remained largely unchanged over the last two centuries, despite significant advances in understanding of the processes involved. The majority of these furnaces are of traditional design, producing a massive quantity of waste due to stains in the parent material. The issue of slag disposition is becoming more acute as free land becomes more scarce, posing a serious challenge to the foundry industries. Concrete has become a significant economic development element for nations all over the world due to the rise in its use caused by rising industrialization. In accordance to recent data from the United States geological survey, forty thousand one hundred MMT of cement are generated globally each year, which translates to a consumption of roughly twenty-seven billion MT of concrete. Fine aggregate makes upto 30–40% of the overall volume of concrete, having a substantial negative impact on natural resources. For the future expansion of the construction industry, efforts are being made to seek alternative of sand due to shortages of sources of fine aggregates as a result of ongoing quarrying and an increase in transportation costs.

"Slag is a non-metallic melt consisting of mixture of oxides and sulphides that were not reduced in the furnace aggregate. The chemical and mineralogical composition of the slag and its temperature determine its physical and chemical properties that affect the slag efficiency. Cupola slag is formed as a by-product in the production of cast iron in cupola furnace. The slag develops as a molten liquid melt and is a composite solution of silicates and oxides that solidifies upon cooling. its amount is 40-80 kg per 1 ton of cast iron produced, and is one of the reasons why this material is not as preferred as blast-furnace slag" A. Pribulova et al. [2]. A practical method for minimising the usage of aggregates and making concrete production environmentally and economically efficient is to partially replace them with solid waste products or industrial by-products. Waste materials are readily available everywhere, which presents an option to use them in place of aggregates for making concrete Balaraman et al. [14]. There are handful of studies in the literature on the viability of using cupola slag as replacement to natural aggregates or cement in concrete.

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Pribulova et al. [10] investigated the feasibility of incorporating cupola slag in place of natural aggregate in the making of concrete. It was reported that the strength parameters of such concretes are not suitable for highly stressed road concretes, and are capable for typical grades of concrete only. It was also reported that these concretes can be used in the core portions of framed structures as well as the bases or levelled surfaces of foundations and buildings. Afolyan and Alabi [8] while investigating the potentiality of cupola mixed concrete observed an increment in compressive strength of modified mixes related to normal concrete. Arum et al. [18] explored the potential of granulated slag as partial replacement of OPC in the production of impervious concrete. They reported a progressive improvement in compressive strength with increase in both age as well as percentage replacement. They also noted a decline in concrete's porosity, demonstrating the material's applicability for harsh environments where minimal permeability is required. Chandiya et al. [15] conducted an experimental study on strength parameters by replacing the coarse aggregate upto 50% by cupola slag. They observed an increment in compressive strength and a drop in tensile strength with increasing percentage inclusion. They also reported decline in permeability as the proportion increases. Chaudhary et al. [16] Conducted an investigative analysis on strength parameters of concrete by partial inclusion of cupola slag. They reported a remarkable increase in strength upto 20% incorporation and a downfall in strength thereafter. They also concluded that the disposing slag in unfolded areas cause environment pollution, which when can be reprocessed and used in construction industry.

II. RESEARCH SIGNIFICANCE

Foundry industry generates huge amount of by-products (waste) every year and there is shortage of waste disposal sites. On the other hand, construction industry depletes natural aggregates at a faster rate which is a big challenge to sustainable development. Recycling and reuse of these by-products are is necessary from the environmental protection point of view and efficient consumption of resources. The aim of this study is to partially replace natural fine aggregate by cupola slag in concrete and to enhance their mechanical and durability properties. Also the aim is to perform SEM (Scanning Electron Microscope) analysis of cupola slag. It is reckoned that partial inclusion of coarse aggregate with cupola furnace slag enhance the strength parameters of concrete. In essence, this study is expected to be worthwhile for various stakeholders who intend to incorporate cupola slag in place of fine aggregates in concrete for various applications. Following flow chart depicts the methodology used in the research.

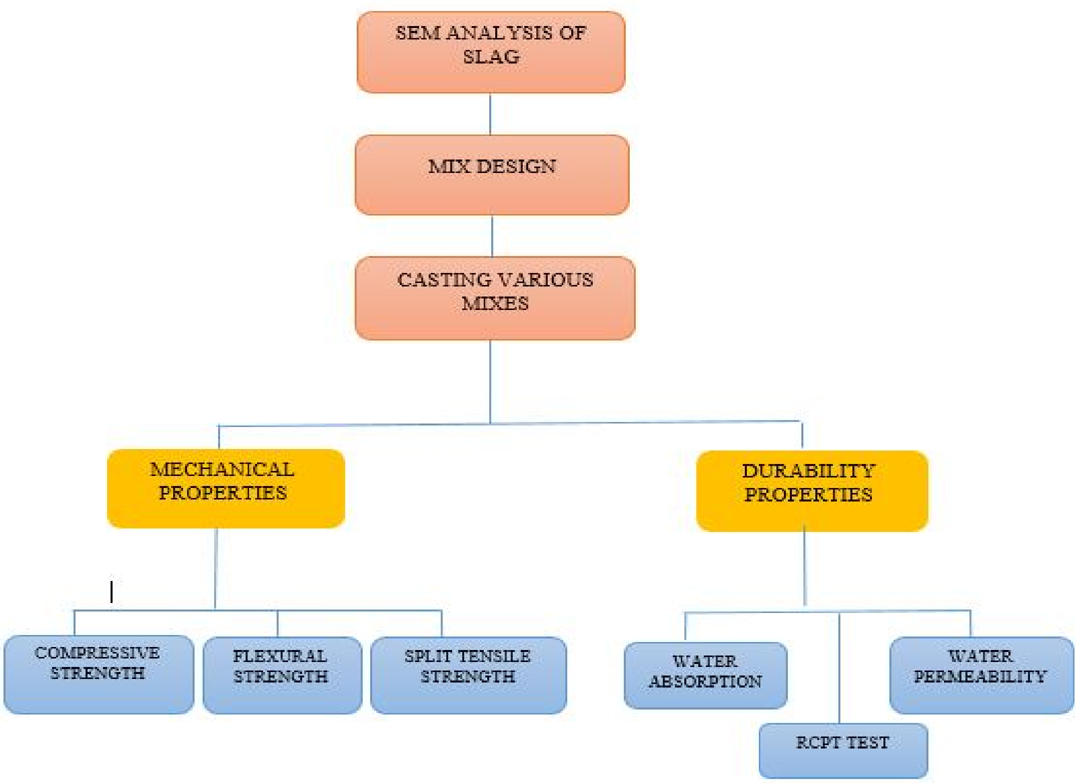

Figure 1. Research Methodology Plan

III. EXPERIMENTAL PROGRAMME

A. Materials

In the current study, ultratech cement of grade OPC-43 complying the requirements of IS 8112 [21] was employed as a binder. The cement was made sure to be brand-new and devoid of any bulges. Tests were performed out to ascertain its different characteristics, and their outcomes are shown in Table 1.

Table 1. Physical properties of Cement

S.No.	Characteristics	Values obtained	Values as per IS 8112 : 1989
1.	Consistency	29.5%	
2.	Initial setting time	108 min	Not less than 30 minutes
3.	Final setting time	242 min	Not more than 600 minutes
4.	Fineness	350 cm^2/gm	Not less than 225 cm^2/gm
5.	Specific gravity	3.15	
6	Compressive strength at 3, 7 and 28 days	25.4, 37.38 and 48.53 N/mm^2	

The natural coarse aggregates are typically composed of broken stones. The work that needs to be done determines the maximum size of coarse aggregates. Crushed and angular coarse aggregates with maximum sizes of 12.5 mm and 20 mm were used in this study since they were readily available from a local source. Coarse aggregates were graded in accordance with IS: 383-1970 [22]. Two distinct coarse aggregates, with nominal sizes of 20 mm single size and 12.5 mm graded, were combined in a 2:1 grading ratio to achieve required grade. Fine aggregates comprise of crushed stone granules passing through a 4.75 mm sieve. Natural sand is used as a fine aggregate in most cases. Crushed stones can be used for fine aggregates in places where natural sand is not available. This study made use of natural sand obtained from nearby sources and conforming to IS: 383- 1970. Table 2 shows the properties of fine aggregates. Cupola furnace slag used in this study was obtained from Ludhiana, Figure 2 depicts typical slag sample. Slag samples were tested for SEM analysis to ascertain their microstructure. Microscopic study depicts the inner structure of cupola slag, which revealed that it was a relatively homogeneous material with equally dispersed individual oxides. It further said that the basic matrix is made up of silicon, calcium, and aluminium oxides.

Table 2. Physical Properties of Natural Fine Aggregates

S.No	Characteristics	Value
1.	Type	Natural
2.	Specific gravity	2.64
3.	Fineness modulus	3.27
4.	Grading zone	III
5.	Water Absorption	0.4%

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Figure 2. Physical Appearance of Cupola Slag

B. Mix Design

M30 concrete reference mix design was formulated in accordance with IS 10262:2019 [23] guidelines. Other mixes were prepared using different percentage replacements of fine aggregate by cupola slag, such as 10%, 20%, 30%, 50%, and 80%, while keeping the quantities of water, coarse aggregates, and cement constant. In all of the mixes, coarse aggregates were used in a fraction of (2:1, 20mm: 12.5mm). Table 3 shows the details of mix design. The mix was designed with the desired workability of 75mm slump. All of the samples were cast at room temperature. In order to make sure that proper compaction and removal of entrapped air from voids, each sample was casted in three different layers.

Table: 3 Final Mix Proportion (M30)

Cement	FA	CA (20 mm)	CA (12.5 mm)	Water
400 kg/m^3	622 kg/m^3	795 kg/m^3	398 kg/m^3	172 kg/m^3
1	1.555	1.988	0.99	0.43

C. Testing

1) *Mechanical Properties:* According to the criteria of IS 516 [25], 150 mm cubes were casted and tried out in a 3000 KN Compression Testing Machine (CTM) to measure compressive strength. The compression tests were carried out at a loading intensity of approximately 140 kg/cm^2/min in load-control mode, with three identical cubes tested for each mix at curing ages of 28 days. The compressive strength of the concrete was calculated by taking the mean of the observed apex loads. Beams having size of 500*100*100 mm were tested under considerations of IS 516 [25] for flexural strength. Three analogous beams from each concrete mix were tested in a flexural test machine of 100 KN capacity at a loading intensity of 180 kg/min up to failure.

   IS 5816 [26] recommendations were followed while testing cylinders with diameters of 100 mm and height of 200 mm for splitting tensile strength. Identical cylinders were tested in a CTM of capacity 3000 KN for all concrete mixes at a loading intensity of 0.6 KN/S until collapse.
2) *Durability Properties:* As per the provisions of ASTM C 642-97 [29], water absorption test was conducted on 100 mm cubes. After 28 days of curing, cubes were taken out from the curing tank and placed in an open environment to dry. After 24 hours of oven drying, the cubes were removed and cooled to room temperature before being weighed. The cubes were placed in the curing tank for 48 hours at a temperature of approximately 210 degrees Celsius. After 48 hours, the cubes were removed and surface dried before being weighed again. Water absorption was calculated using the average of three specimens from each type of mix.

Water permeability test was conducted on 150 mm cubes as per the provisions of DIN 1048 (Part 5)/ EN 12390-8 [31]. The reservoir was filled to 75 percent capacity, and the concrete specimens were positioned inside the penetration cell. Water regulator's valve was opened, and the pressure regulator was used to open the pressure valve, keeping the pressure at 5 kg/cm2. The samples were placed inside the penetration cell for 72 hours. After three days, the samples were removed from the penetration cell and placed under the CTM. The samples were splitted vertically to the injected face, penetration depth was measured visually.

Rapid chloride permeability test was conducted in accordance with ASTM C1202-12 [27], which indicates its resistance to chloride ions penetration. A cylinder of 100mm diameter and 200mm height was cut into slices of 100mm diameter and 50mm height to make the samples for this test. The prepared specimens were fed into the vacuum desiccator's bowl and the vacuum inside the bowl was maintained for at least 3 hours. The flow of de-aerated water inside the vacuum desiccators was permitted because it completely covered the concrete samples, and air entry was prohibited. The specimen was removed from the bowl and dried on the surface. Specimens were mounted into the gasket after they had dried on the surface. Two solutions were fed into each testing mould. During this 6-hour test, the quantity of electrical charge passing through the specimen was measured. The electrical charge passed determined the chloride ion permeability of the concrete prototype.

IV. RESULTS AND DISCUSSION

A. *Compressive strength*

The results of compressive strength for all percentage replacements are presented in Table 4 and are represented in the form of bar chart shown in Figure 3.

Table: 4 Average Compressive Strength

S.no	Type of Mix	Average Compressive Strength (MPa) at 28 days
1	Control Mix	36.5
2	10% CS Mix	37.4
3	20% CS Mix	38.1
4	30% CS Mix	38.7
5	50% CS Mix	37.5
6	80% CS Mix	34.6

It was observed that compressive strength showed an increase of 2.46%, 4.38%, 6.02% and 2.7% on 10%, 20%, 30% and 50% CS replacement respectively as compared to control mix. However, on 80% CS replacement it showed a decrement of 5.47% in comparison to control mix. These results further reveal that the increasing trend goes up to 30% CS replacement and shows a downfall thereafter.

Therefore, we can conclude that 30% fine aggregate replacement by cupola slag is optimum. In accordance with Sosa et al. [17] while performing microstructural tests on concrete specimens including slag from induction furnaces and cupola furnace, cupola slag fragments respond and combine properly in paste by creating composites that resemble parallel hexagonal plates, with these plate composition being consistent with hydrated calcium aluminosilicates. The findings observed are similar to that of Sosa et al. [17] who as well noted a rise in strength due to augmentation of cupola slag.

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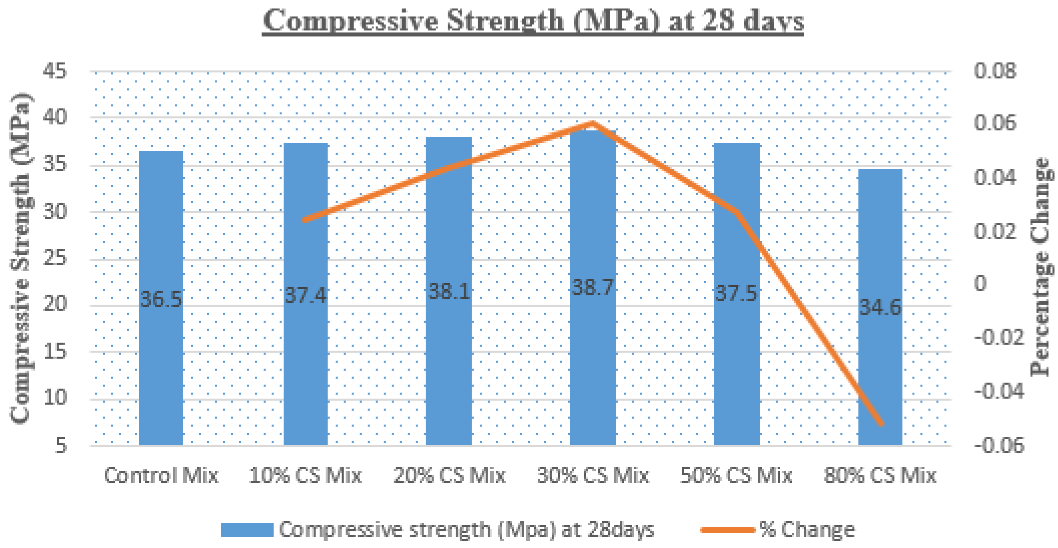


Figure 3. Compressive Strength at 28 days

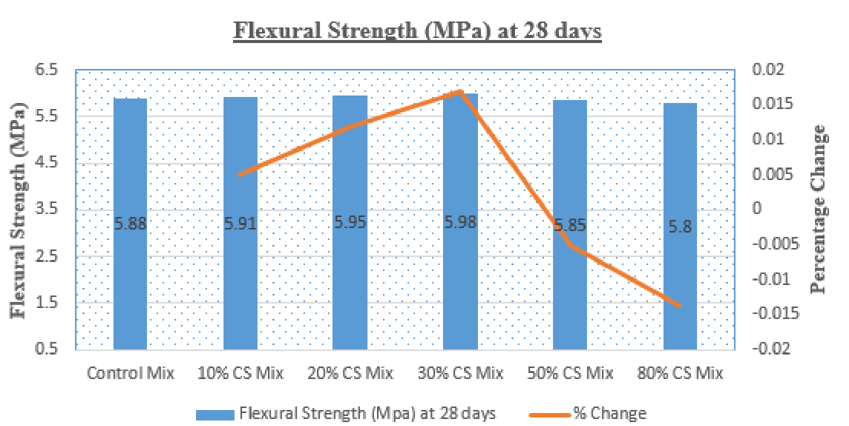
B. Flexural Strength

The observed outcomes of flexural strength for various percentage incorporations of cupola slag are presented in Table 5 and are shown in the form of bar chart in Figure 4.

Table 5.Average Flexural Strength

S.no	Type of Mix	Average Flexure Strength (MPa)
1	Control Mix	5.88
2	10% CS Mix	5.91
3	20% CS Mix	5.95
4	30% CS Mix	5.98
5	50% CS Mix	5.85
6	80% CS Mix	5.8

Figure 4. Flexural Strength at 28 days



An increase of 0.5%, 1.1%, and 1.7% was observed in flexural strength on 10%, 20%, and 30% CS replacement, whereas on 50% and 80% CS replacement it showed a decrease of 0.51% and 1.3% respectively as compared to control mix. These results further show that the increasing trend goes up to 30% CS replacement and shows a decrement in strength thereafter on further replacement by cupola slag.

C. Split Tensile Strength

Table 6 below depicts the split tensile strength of various cupola inclusions and their variation is depicted in Figure 5.

Table 6. Average Split Tensile Strength

S.no	Type of Mix	Average Split tensile Strength (MPa) at 28 days
1	Control Mix	4.06
2	10% CS Mix	4.27
3	20% CS Mix	4.35
4	30% CS Mix	4.55
5	50% CS Mix	4.25
6	80% CS Mix	3.76

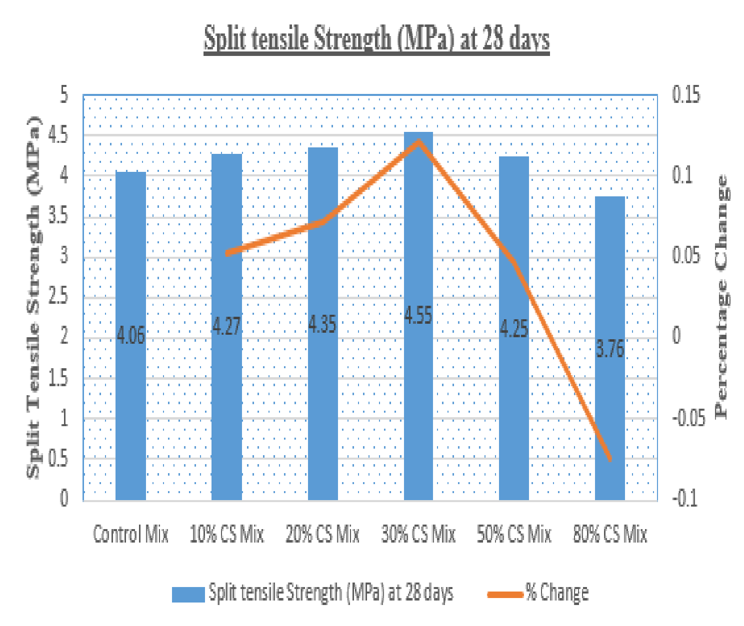


Figure 5. Split Tensile Strength at 28 days

It is observed that the split tensile strength of different concrete mixes goes on increasing up to 30% substitution only, which is in general pertinent to all strength parameters in the current study.

Following that, a reduction in split tensile strength is seen with further inclusion of cupola slag. Split tensile strength showed an increase of 5.1%, 7.1%, 12.06% and 4.67% on 10%, 20%, 30% and 50% CS replacement respectively and on 80% CS replacement it showed a decrement of 7.3% as compared to control mix. The influence is remarkably identical to which was noticed in compressive strength. Furthermore, it is evident that the rate of change of split tensile strength increase is marginally higher that compressive strength increase.

This increased split tensile strength is imputed to cupola slag's reactive properties, which enhance the bonding between the aggregates in interfacial transition zone [17]. Similar to compressive strength, it was observed that any additional fine aggregate replacement with cupola slag past 30% results in decrement in tensile strength.

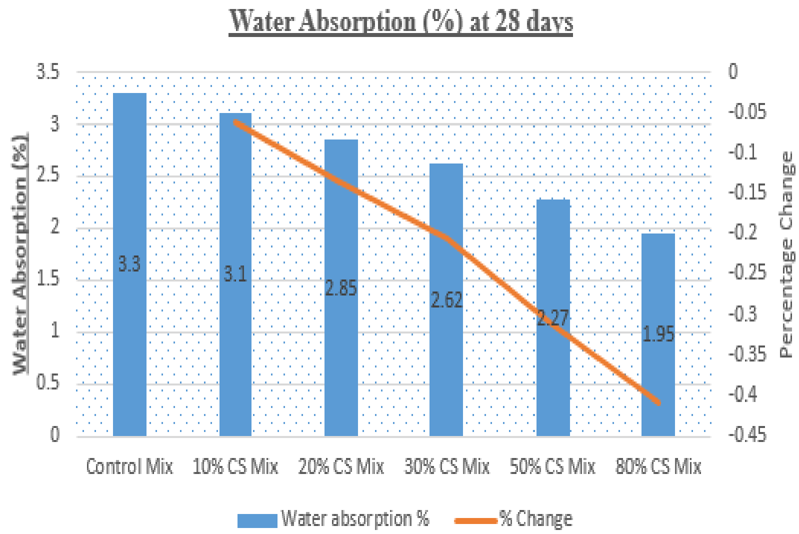


Figure 6. Water Absorption at 28 days

D. Water Absorption

Table 7 and Figure 6 both reflect the results observed while performing the water absorption test.

Table 7. Water Absorption at 28 days

S.no	Type of Mix	Water absorption %
1	Control Mix	3.3
2	10% CS Mix	3.1
3	20% CS Mix	2.85
4	30% CS Mix	2.62
5	50% CS Mix	2.27
6	80% CS Mix	1.95

After 28 days of curing the observed data of water absorption is 3.3%, 3.1%, 2.85%, 2.62%, 2.27%, and 1.95% in the control mix and mixes with varying of 10%, 20%, 30%, 50%, and 80% fine aggregate replacement by cupola slag respectively. While comparing to the control mix, it showed a decreasing trend of 6.06%, 13.62%, 20.6%, 31.21%, and 40.9% respectively in modified mixes. The decrease in water absorption with increasing replacement may be due to the formation of a less porous structure as a result of the addition of cupola slag.

E. Water Permeability

Table 8 shows the observed date of water permeability test and is presented in the form of bar chart in Figure 7.

Table 8. Depth of Water Penetration

S.no	Type of Mix	Depth (mm)
1	Control Mix	19
2	10% CS Mix	17
3	20% CS Mix	15
4	30% CS Mix	12
5	50% CS Mix	9
6	80% CS Mix	5

The depth of penetration shows a decrease of 10.5%, 21.05%, 36.84%, 52.63%, and 73.68% respectively in modified mixes of 10%, 20%, 30%, 50%, and 80% fine aggregate replacement by cupola slag as compared to that of control mix. This decrease in penetration can be linked to concrete's decreased porosity due to cupola slag incorporation, which plugs all the tiny openings present in it. Arum and Mark [11] claims that any increment in inclusion of cupola slag leads to a decrease in voids in concrete and a reduction in permeability.

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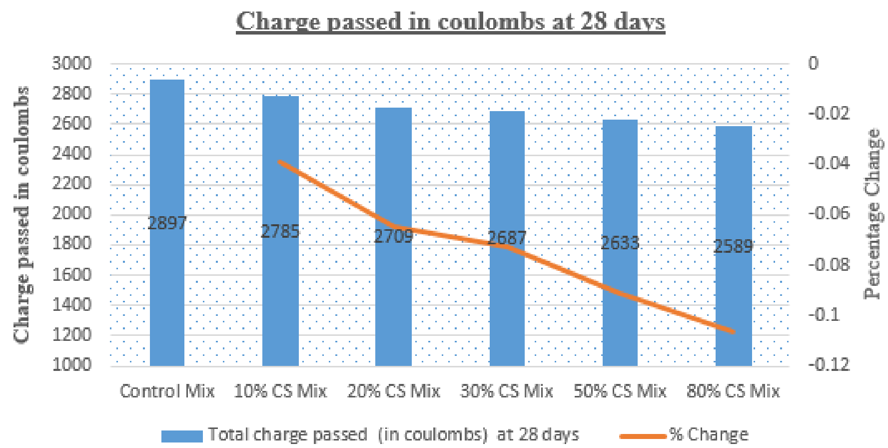

Figure 7. Depth of Water Penetration at 28 days

F. RCPT

The resistance to penetration of chloride ion is expressed as the quantity of electrical charge passed through the concrete sample for a period of 6 hours and the observed data is presented in Table 9 and shown graphically in Figure 8.

Table 9. Total Charge Passed in Coulomb

S.no	Types of Mix	Total charge passed (in coulombs) at 28 days	Permeability as per ASTM C1202-12
1	Control mix	2897	Moderate
2	10% CS mix	2785	Moderate
3	20% CS mix	2709	Moderate
4	30% CS mix	2687	Moderate
5	50%CS mix	2633	Moderate
6	80% CS mix	2589	Moderate

Rapid chloride penetration test followed the same trend as it was observed in the water absorption test with the overall decrease observed to be 7%. The maximum decrease was noted in the mix with 80% CS mix having 11% decrease when compared with control mix.

The least decrease in chloride penetration was observed in 10% CS mix with the decreasing percentage of 4%. The overall decrease can be caused due to the less void volume occurred with better packaging performance of cupola slag.

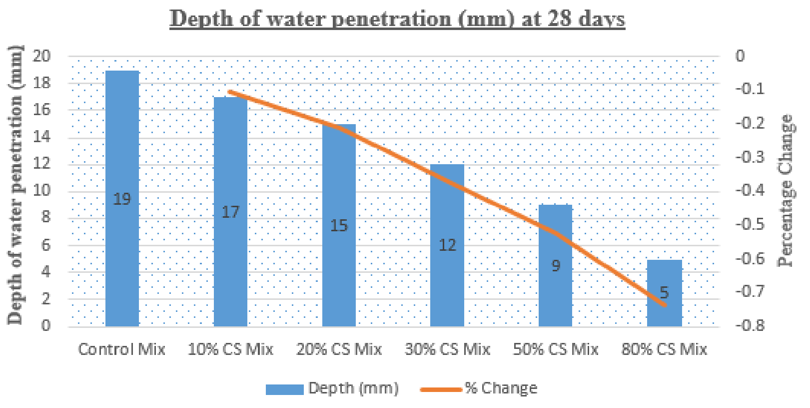

Figure 8. Charge Passed (Coulombs) at 28 days

V. CONCLUSIONS

To ascertain the impact of cupola furnace slag on concrete's strength and durability criteria, experimental testing was done in this study and findings suggest that cupola furnace slag is a endurable matter with the potency to be used in concrete. The following conclusions can be drawn from the noted trends in experimental investigation.

1) An increase in compressive strength was observed up to 30% replacement level of fine aggregate by cupola slag and beyond that a decreasing trend was observed on further accession. The aforementioned pattern can be linked to cupola slag's reactive nature, which when it reacts, produces compounds with a composition similar to hydrated calcium aluminosilcates.
2) Similar trend was observed for other strength parameters like flexural and split tensile strength.
3) Compared to ordinary concrete the modified concrete showed lower values of water absorption and goes on decreasing as the percentage replacement increases.
4) For water permeability same trend was observed as that in water absorption i.e., a reduction is seen for all cupola slag replacements. This trend can be linked to concrete's decreased porosity due to cupola slag incorporation, which fills all the tiny pores present in it.
5) Rapid chloride penetration test followed the same trend as it was observed in the water absorption and water permeability tests with overall decrease observed to be 7%. The overall decrease can be caused due to the less void volume occurred with better packaging performance of cupola slag.
6) For strength point of view optimum percentage replacement was found to be 30%.

Therefore, to conclude results in a gist, replacing natural sand by cupola slag results in increase in strength parameters up to a certain percentage and it also leads to decrease in water absorption, permeability and chloride ion penetration of concrete which when improves its durability.

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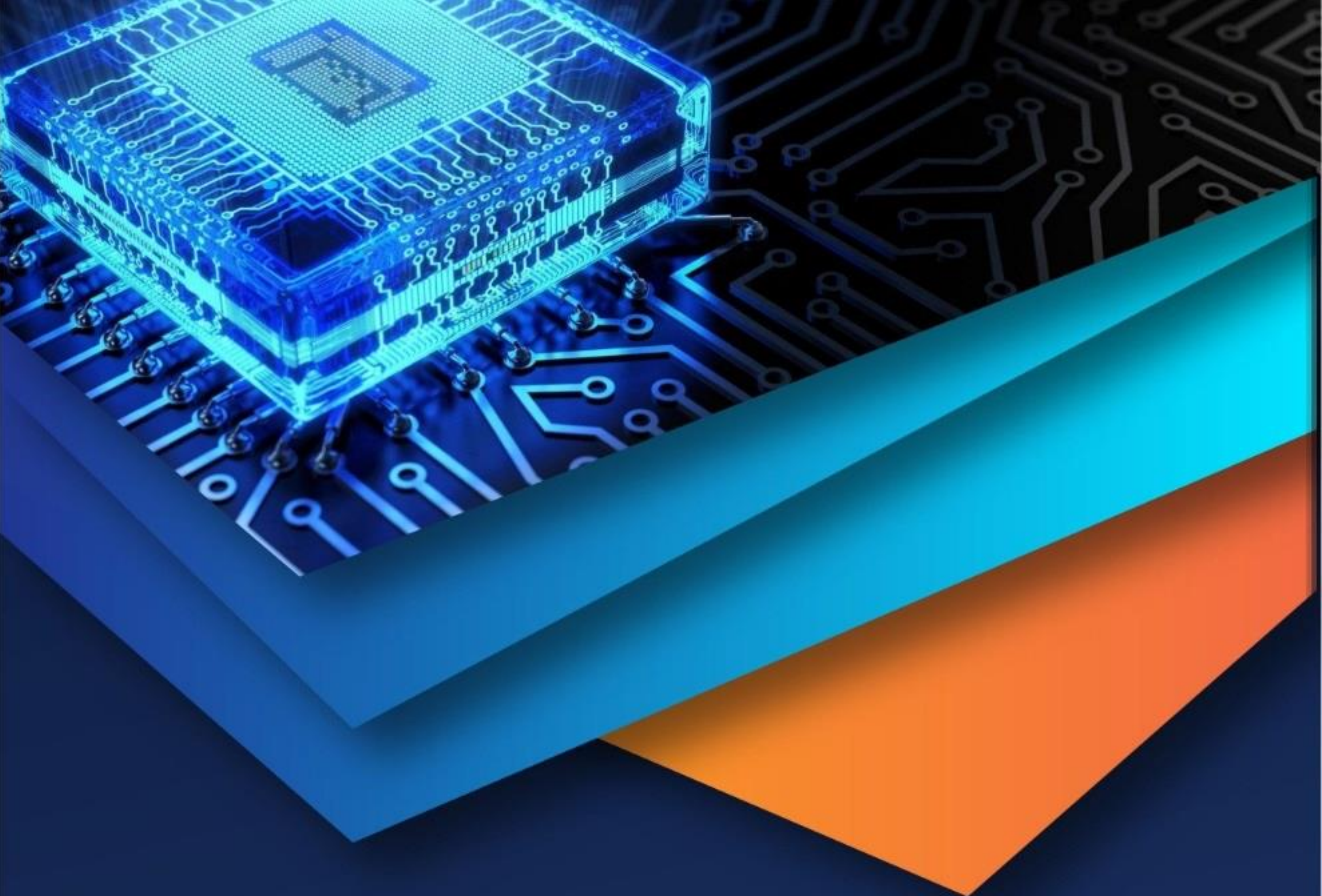

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